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# The solidification of squeeze cast AlCu4Ti alloy

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## Abstract

The results of examining the solidification process of the squeeze cast AlCu4Ti alloy have been presented. A simulation of the alloy solidification has been described for both the equilibrium conditions taking into account squeeze pressure and the non-equilibrium conditions under the assumption of the lack of diffusion in the solid state (Scheil model). Experiments have been held for plate castings squeezed under the pressure ranging from the atmospheric one to the value of 90 MPa. The derivative differential thermal analysis (DDTA) method has been used for determining the phase transition point, solidification rate and the degree of alloy supercooling dependent on the squeeze pressure. It has been found that the solidification rate is increased by almost seven times for squeeze castings as compared with the gravity castings. Squeezing causes also a significant refinement of the alloy dendritic structure and removes gas and shrinkage porosity, characteristic for die castings. The high quality AlCu4Ti-alloy castings can be obtained already at the 30 MPa pressure.

**Keywords: S**queeze casting, AlCu alloys, Solidification, Structure

## 1. Introduction

Crystallization of metals and alloys under external pressure is usually analysed in terms of thermodynamics. The influence of pressure on the phase transition points, changes of mutual solubility of the alloy components, and formation of the high-pressure phases can be estimated on the basis of the thermodynamic relationships [1-5]. These analyses concern, however, only the small range of binary systems.

The currently presented ideas [1, 4-6] do not give a consistent explanation to the problems of nucleation and crystal growth under the high pressure conditions. It results mainly from the experimental difficulties occurring at the assessment of the crystallization kinetics. The prevailing theory says that the great amount of nuclei, and by the same the high degree of the grain refinement, is caused by the supercooling increase resulting from the high-rate heat transfer in the casting-die system for squeeze casting. If a casting solidifies under external pressure, the shrinkage gap occurs relatively much later than for a common die casting solidification. Moreover, plastic deformation of the casting and the resulting adherence to the die can occur at very high pressure values, thus enabling high-rate heat losing for the entire solidification period. The degree of liquid metal supercooling is correlated with the squeeze temperature. Applying the pressure at a temperature close to the solidification temperature seems to be the most effective [1, 5] because in this case the maximum supercooling occurs as well as the greatest increase in the nucleation rate. On the other hand, the excess overheating of the alloy can completely nullify the beneficial effect of the increased pressure. This pressure causes also an increase in the heat transfer coefficient and some changes in the diffusion processes; the activation energy rises while the diffusion coefficient decreases [1, 7]. The squeeze castings exhibit considerable dimensional accuracy and surface smoothness, do not indicate shrinkage macro- or microporosity, and their mechanical properties often exceed those achieved by the plastic worked material [8-15].

The purpose of the presented investigations has been the assessment of the solidification kinetics of the squeeze cast AlCu4Ti alloy and the determination of the squeeze pressure influence on the phase transition point, solidification rate, and the degree of alloy supercooling.

## 2. Examined material and methodics of investigation

The commercial AM5 alloy (AlCu4Ti alloy) has been examined, its chemical composition being as follows: 94.51% Al, 4.35% Cu, 0.34% Mg, 0.23% Ti, total percentage of impurities (Fe, Si, Zn, Mn, Ni) – 0.57%. The metal has been melted in the PIT 50S/400 induction crucible furnace. Plate specimens have been cast in the die of cavity dimensions 0.2 × 0.1 × 0.05 m mounted on the PHM-250C hydraulic press. Squeeze casting process has been realised at a constant pouring temperature equal to about 700°C and the die temperature of 200°C – 230°C. Castings have been made at the following values of the applied pressure: atmospheric, 30 MPa, 60 MPa, and 90 MPa. The examination of the solidification process have been done by means of the DDTA method at the Crystaldigraph PC stand using two coated NiAl-NiCr thermocouples of 1.5 mm diameter. One of them has been placed in the die at a distance of 10 mm from the cavity surface (measurement of the die temperature) and the other in the thermal centre of the plate (DDTA investigations). Sampling time has been 0.2 s. Observations of microstructures have been held by means of the optical microscope EPIPHOT made by NIKON.

## 3. Initial examination – simulation of the solidifying process

The calculation packet THERMO-Calc, version M, provided with SSOL database has been used for simulation of solidification of the examined AlCu4Ti alloy. The SSOL database contains thermodynamic data for binary, ternary, and multi-component alloys.

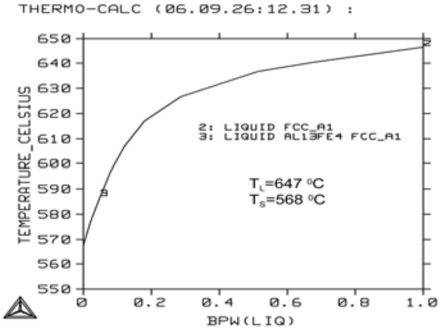


Fig. 1. AM5-alloy solidification curve for equilibrium conditions

Simulations have been performed for both the equilibrium conditions taking into account the squeeze pressure and the non-equilibrium conditions under the assumption of lack of the diffusion in the solid state. The phase transition points have been found for the alloy, as well as changes of phase composition against the temperature. The simulation results are shown in Figs 1-3.

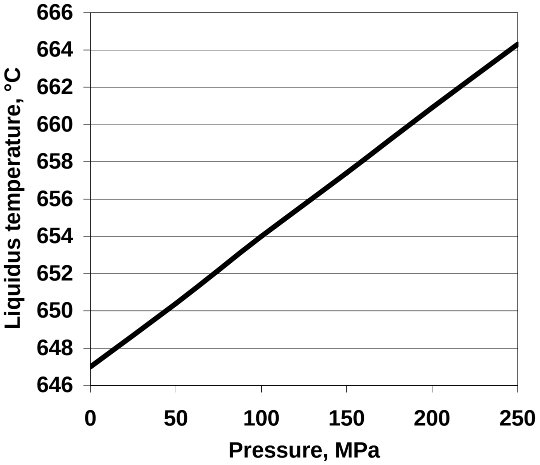
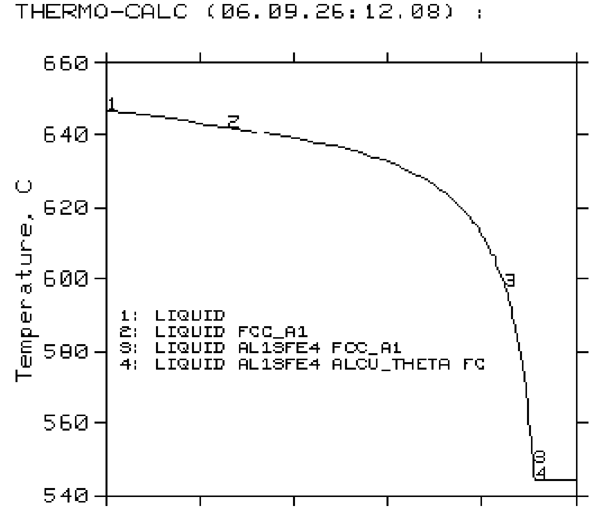


Fig. 2. The influence of pressure on the AM5-alloy liquidus temperature according to the Clapeyron-Clausius relationship



| Point | Temp. °C | Phase composition of the alloy |
|---|---|---|
| 1 | over 647 | liquid |
| 1-2 | 647 – 640 | liquid + α phase |
| 2-3 | 640 - 545 | liquid + α phase + $Al_{13}Fe_4$ |
| 4 | 545 | α phase + $Al_{13}Fe_4$ + $Al_2Cu$ |

Fig. 3. AM5-alloy solidification curve according to the Scheil model

It results from the performed simulations that the liquidus temperature for the examined alloy is equal to 647°C. The alloy under the equilibrium conditions crystallises as a single phase containing $Al_{13}Fe_4$ impurities (Fig. 1), while if the solid state diffusion is lacking, the ($\alpha$ + $Al_2Cu$) eutectic additionally occurs due to the segregation. Also the solidus temperature is changed from 568°C for the equilibrium crystallization to 545°C for the non-equilibrium one (Fig. 3). The dependence of the liquidus temperature on pressure depicted in Fig. 2 indicates that for maximum squeezing pressure of 90 MPa used during the experiment the equilibrium transition point is increased by 6°C.

## 4. Experimental results

Fig. 4 presents the exemplary cooling curves T(t) and solidification curves (dT/dt) for AM5 alloy along with the die temperature change $T_F(t)$, while the Table 1 puts together data concerning phase transition points and kinetic parameters corresponding to the applied squeeze pressure values.

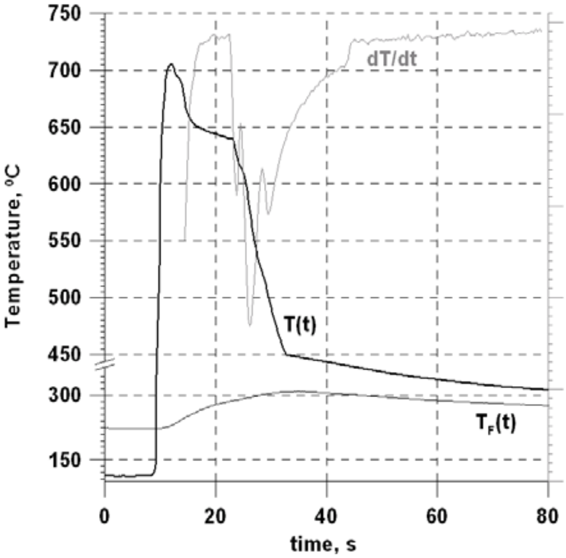


Fig. 4. Cooling curve T(t), solidification curve (dT/dt) for AM5 alloy under the squeeze pressure of 30 MPa, and the die temperature curve $T_F(t)$ (about 225°C prior to pouring)

Table 1.
Temperature and kinetic parameters of AM5 alloy solidification determined by the DDTA method

| Pressure | Solidification temperature of, ˚C | | | Solidification time $t_k$, | Average solidification rate dT/dt, |
|---|---|---|---|---|---|
| MPa | α phase, $T_\alpha$ | ferrous phase $Al_{13}Fe_4$, $T_{FŻ}$ | eutectic α +$Al_2Cu$, $T_{eut.}$ | s | °C/s |
| atm. | 643 | 617 | 525 | 54 | 2,1 |
| 30 | 645 | 625 | 522 | 14 | 8,8 |
| 60 | 648 | 620 | 520 | 10 | 12,9 |
| 90 | 650 | 620 | 504 | 8 | 18,85 |

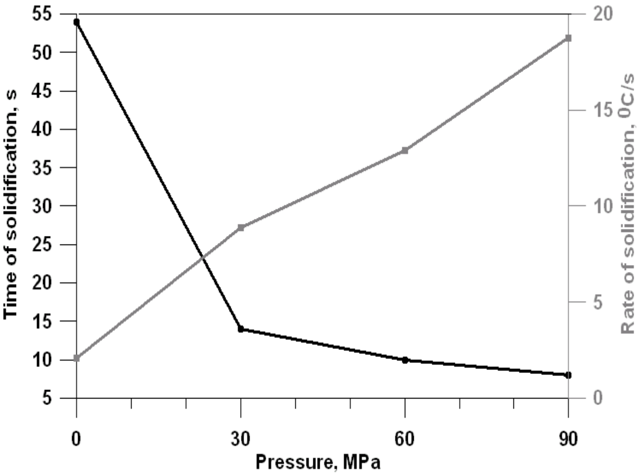


Fig. 5. Influence of pressure on solidification time and the average solidification rate of experimental plate casting made of AM5 alloy

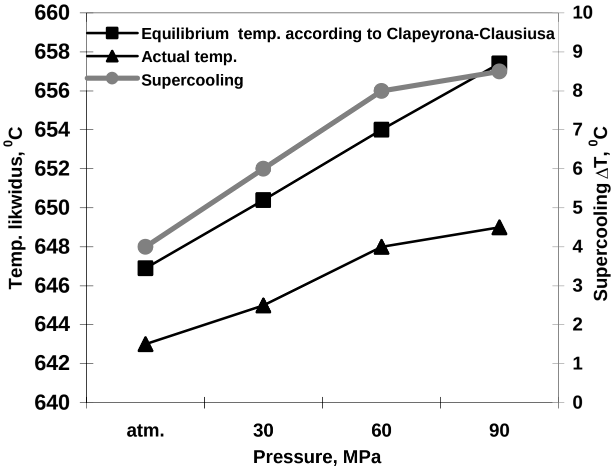


Fig. 6. Influence of pressure on the liquidus temperature and the supercooling of AM5 alloy

Squeezing of the liquid alloy increases the rate of heat exchange in the die-casting-plunger die system. This results in the change of kinetic parameters of the solidification process, the solidification time is reduced and the rate of the process increased (Fig. 5). The solidification time for gravity castings is about 54 s, while squeeze castings made under the pressure of 90 MPa solidify in 8 s, what gives an increase of the average alloy solidification rate to the value of about 19 K/s.

Crystallization of alloy under external pressure begins with the dynamic nucleation. The mechanism of this process is explained by arising and closing of voids. While a void is being closed, the pressure in the liquid metal grows, thus enabling formation of a nucleus in a higher temperature, however the pressure value has no influence on the supercooling degree ΔT. The supercooling of the alloy is the same both under the atmospheric and under the increased pressure [6]. Fig. 6 illustrates change of the equilibrium and the actual solidification temperature along with the supercooling degree versus pressure, estimated on the basis of DDTA examinations. It results from the plot that the supercooling rises proportionally to the squeezing pressure. Such a relationship can be explained by the intensified heat outflow to the die, because the shrinkage gap between the casting and the die is totally or partially eliminated due to squeezing.

Structural changes caused by squeezing have been presented in Fig. 7. The AM5 alloy has a dendritic structure which morphological properties are related to the casting process conditions. The size of α-phase crystals in squeeze castings is significantly less than in gravity castings.

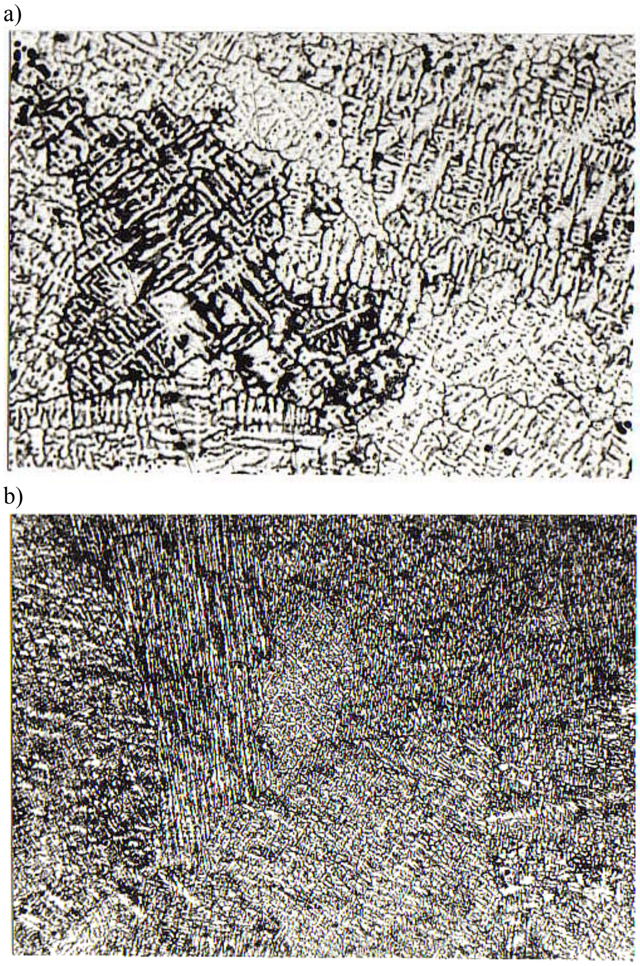


Fig. 7. AM5 alloy structure: a) gravity casting b) squeeze casting for 90 MPa pressure applied, magn. 50×

Within the pressure range of 30 - 90 MPa the difference with respect to the refinement degree are not so distinct. The squeezing technology has ensured obtaining castings free of internal defects. The shrinkage and gas porosity characteristic for gravity casting is totally eliminated already at the squeezing pressure of 30 MPa.

## 5. Analysis of results and final conclusions

1. Submitting the AlCu4 alloy to the squeeze casting process leads to the significant changes in the solidification process kinetics. Eliminating the shrinkage air gap between the liquid metal and the die results in the average solidification rate for squeeze castings being increased by almost 7 times as compared with gravity castings.
2. An effect of the intensive heat transfer is the growth of the alloy supercooling, which increases proportionally to the squeezing pressure. For the examined plate castings the maximum supercooling has occured at the pressure of 90 MPa and has been equal to 9ºC.
3. Squeezing causes the refinement of the dendritic structure of the AlCu4Ti alloy and eliminates porosity thus increasing the density and the pressuretightness of castings.

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